CELSS

NASA Conference Publication 2231

Controlled Ecological Life Support System

Use of Higher Plants

Proceedings of two NASA workshops held at the O'Hare Airport Conference Center Chicago, Illinois, November 1979 and at the Ames Research Center Moffett Field, California March 1980

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Controlled Ecological Life Support System

Use of Higher Plants

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PREFACE

This report has been developed by a group of 27 crop physiologists that met in two separate workshops held in Chicago, IL, November 1979 and Moffett Field, CA, March 1980. The recommendations and conclusions presented in this report represent a unified consensus of this group.

The purpose of the workshops was to consider the use of higher plants in Controlled Ecological Life Support Systems (CELSS). The results of the workshops are intended to contribute to the development of a comprehensive program plan for NASA's Biological Systems Research program.

The excellent discussions that ensued and the harmonious accord that was obtained at the workshops were due in large measure to the following physiologists who provided direction and chaired separate sessions: Johan Hoff, Tak Hoshizaki, Bob Langhans, Doug Ormrod, Ralph Prince, Dave Raper, Frank Salisbury and Herb Ward. A special thanks to Ben Zietman and Pete Zill for logistics and coordination at NASA/Ames. These workshops were supported by NASA under Grant No. NSG 2405.

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I. INTRODUCTION

The use of higher plants for food production has been proposed for long duration or large scale manned space missions to minimize the prohibitively large storage and resupply costs (Mason and Carden 1979; Spurlock et al. 1979; Johnson and Holbrow 1977) associated with carry-on food and oxygen. There is no consensus on the break-even point (weight) in flight duration for a contained life support system compared with food storage or resupply alternatives. The break even point has been variously described as anywhere from 30 days to 12 years (Space Science Board 1969; Ward et al. 1963). Estimates vary widely due to incomplete analyses and well recognized difficultires encountered in extrapolation from theoretical models and experimental data (Ward et al. 1963). A major deficiency has been lack of data for maximum food producing capability of plants and the minimum weight requirements for maintaining plants in sustained growth systems.

Initial efforts toward development of food production systems for manned spacecraft were initiated by both the United States and the Soviet Union during the late 1950's and early 1960's. Systems were planned for both orbital and moon-based stations (Taub, 1974). Significant funds were committed to study the use of different kinds of life support systems, including algae, particularly Chlorella (Dole 1964; Drake 1966; Gitel'son et al. 1975; Miller and Ward 1966; Ward et al. 1963), Hydrogenomonas (Drake 1966), various species of duckweed (Ward et al. 1963), and physiochemical systems lacking biological components (Dole 1964). Major emphasis was placed on developing continuous production algal systems, since they use growing space efficiently, produce oxygen, are rich in protein, may be used as food supplements, and are also efficient in processing metabolic wastes. However, productive algal systems have been difficult to maintain for long periods of time, do not provide a balanced palatable diet and require cumbersome maintenance and harvesting procedures (Dole 1964).

It has been proposed by the Space Science Board of the National Academy of Sciences (1969) that multiorganism systems (plants and algae) should be employed for food and oxygen production in future space efforts. This would provide two support systems, so that if one failed or was inoperative for a period of time, production of both food and oxygen would continue.

Higher Plants

Higher plants can provide most, if not all, of the major food needs of man; calories, proteins, fats and carbohydrates; along with the much smaller requirements for minerals, vitamins and trace elements (Table 1). The nutritional value of the major U.S. plant foods expressed on a 100 g edible portion is indicated in Tables 2a, 2b and 2c. The nutritional value contained in individual servings in Tables 3a and 3b. In addition, higher plants can provide all of the oxygen required for life support in manned spacecraft and recycle waste water. The daily food, oxygen and water requirements for man are shown in Table 4. It has been variously estimated that anywhere from $4m^2$ (Dadykin 1968) to $250m^2$ (Dole 1964) of hydroponically grown plants are required to provide the life support requirements for one man.

Heydecker (1973) expressed concern that plants produce seeds with low viability when grown for several generations in controlled environments and that the edible portions will not be as nutritious or as productive as field grown plants. However, Gitel'son *et al*. (1975) reported that cultivars reproduced up to 10 generations of healthy plants in controlled environments without deterioration of vigor. Similarly, Gitel'son *et al*. (1975) compared protein, fat, vitamin and mineral content of field and phytotron grown beets, radishes, turnips and onions and found in all cases, nutritional levels in phytotron-grown plants were comparable or better than field-grown plants (Table 5). It is generally recognized by crop physiologists that the nutritive value of plants grown in controlled environments varies considerably and has nutritive value that is simi-

Table 1

DAILY DIETARY RECOMMENDATIONS AND PRACTICES

NUTRIENT	NRC[1] (RDA)	FAO/WHO[2]	SKYLAB[3]	Veg.[4]
Energy (kcal)	2700 (2300-3100)	3000	2700 (2300-3100)	1970
Protein (g)	56	37-62	90-25±10	65.4
Vit. A (mcg R.E.)	1000	750	1000	2102
Vit. D (mcg)	5 (200 I.U.)	100 I.U.	5 (200 I.U.)	-
Vit. E (mg Alpha T.E.)	10	-	10	-
Vit. C (mg)	60	30	60	180
Thiamin (mg)	1.4	1.2	1.4	1.9
Riboflavin (mg)	1.6	1.7	1.6	1.2
Niacin (mg)	18	19.8	18	18
Vit. B_6 (mg)	2.2	-	2.2	-
Folacin (mg)	400	200	400	-
Vit. B_{12} (mcg)	3	2	3	0
Calcium (mg)	800	400-500	750-850±16	594
Phosphorus (mg)	800	-	1500-1700±120	1368
Magnesium (mg)	350	-	300-400±100	-
Iron (mg)	10 (man)	9 (man)	10 (man)	19
	18 (woman)	28 (woman)	-	
Zinc (mg)	15	-	15	-
Iodine (mcg)	150	-	150	-
Sodium (g)	1.1-3.3		3.0-6.0±0.5	2.2
Potassium (mg)	1525-4575		2740 min. no max. and no range	4100

[1]Reference man 70 kg mixed diet (Nat. Acad. Sci. 1980)

[2]Reference man 65 kg mixed diet (FAO 1967, FAO 1970b, FAO 1973)

[3]Mixed diet (Klicka _et al_. 1967)

[4]VEG: Average calculated values of a 14-day vegetarian cycle menu which was developed from communication with practicing strict vegetarians; and adapted from "Recipes from a Small Planet" (Robertson _et al_. 1978) and "Laurel's Kitchen, a handbook for Vegetarian Cookery and Nutrition" (Ewald 1977). Soybean meal values were substituted for milk and milk products. Soybean lecithin values were used in place of egg in mayonaise, etc.

Table 2a

COMPOSITION OF SELECTED PLANT SPECIES[1]

General

(Amount in 100g Edible Portion-Dried)

Species	Calories	Prot	Fat	Ash	CHO	Fiber
		(grams)				
Soybean	466	37	19.5	5.0	38	8.6
Dry Bean	386	24	1.8	4.4	70	4.5
Split Pea	382	27	1.1	3.1	69	1.3
Podded Pea	317	20	1.2	6.6	72	7.2
Chick Pea	403	23	5.4	3.4	68	5.6
Peanut	585	28	45	2.8	24	2.5
Rice	409	8.5	1.9	1.3	88	.7
Wheat	379	16	2.5	2.0	79	2.6
Oats	425	16	8.1	2.1	74	1.3
Corn	411	10	3.9	1.3	85	1.1
Potato	373	9	.5	5.4	86	1.8
Sweet Potato	290	6	2.2	3.5	89	3.2
Beet Greens	338	13	.8	8.9	77	7.3
Lettuce	288	23	3.8	17.3	56	11.5
Spinach	274	32	4.1	20.5	44	8.2
Mustard Greens	295	29	4.8	13.3	53	10.5
Kale	298	29	4.5	12.7	54	9.0
Tomato	339	17	5.1	10.2	68	10.2
Strawberry	366	7.9	5.0	5.0	82	13.9
Onion	366	11.4	1.6	4.9	84	0.8
Cucumber	308	17.9	2.6	10.3	69	12.8
Broccoli	287	32.7	2.0	10.9	54	12.9
Sugar Beet	320				80	4.0

[1]Proximate analysis obtained from Watt and Merril (1963).

Table 2b

COMPOSITION OF SELECTED PLANT SPECIES[1]

Vitamins

(Amount in 100g Edible Portion-Raw)

	A (IU)	B_1 (mg)	B_2 (mg)	B_7 (mg)	B_6 (mg)	Fol (μg)	Pan (mg)	Bio (μg)	C (mg)	E (mg)	Car (mg)
Soybean	80	1.1	.3	2.2							
Dry Bean		.7	.2	2.4	.6		.7			2.3	
Split Pea		.7	.2	3.2	.1	33	2.0				
Podded Pea		.2	.1	.9	.2	25	.8		36	2.7	
Chick Pea		.5	.15	1.5		180					190
Peanut		.9	.1	16	10.5	110	2.7		3	8.1	
Rice		.3	.05	4.7							
Wheat		.5	.1	4.7	.6		.8			2.3	
Oats		.5	.1	1.0	.1	60	1.0	20		.8	
Corn	510	.4	.1	2.0	(.2)[2]	(52)	(.5)			(.8)	(240)
Potato		.1	.04	1.2	.2	10	.2		30	.1	
Sweet Potato	8800	.1	.06	.6					21		
Beet Greens	6100	.1	.2	.4					30		
Lettuce	1900	.05	.08	.4					18		
Spinach	8100	.1	.2	.6					51		
Mustard Greens	7000	.1	.2	.8					97		
Kale	8900	(.2)	(.3)	(2.0)					(125)		
Tomato	900	.1	.04	.7					23		
Strawberry	60	.03	.07	.6					59		
Onion	40	.03	.04	.2					10		
Cucumber	250	.03	.04	.2					11		
Broccoli	2500	.1	.2	.9					113		
Sugar Beet											

[1]Obtained from Watt and Merril (1963).

[2]Estimated values.

Table 2c

COMPOSITION OF SELECTED PLANT SPECIES[1]

Minerals

(Amount in 100g Edible Portion-Raw)

Species	Ca	Mg	Na	K	Cu	Zn	Fe	S	Cl	P
				(milligrams)						
Soybean	226	265	5	1677			8.4			554
Dry Bean	144	170	19	1196	.85	.20	7.8			425
Pea, Split	33	180	38	910	.58	(4.0)[2]	5.4	170	56	270
Pea and Pod	49	35	9	135	.22	(1.3)	1.1			54
Chick Pea	140	160	40	800	.76		6.4	180	60	300
Peanut	61	180	6	680	.27	3.0	2.0	380	7	370
Rice, Brown	32	88	9	214			1.6			221
Wheat, Whole	36	.9	(3)	435	.20		3.1		.4	383
Oats	55	110	33	370	.23	(3.0)	4.1	160	73	380
Corn	22	147	1	284			2.1			268
Potato, White	8	34	7	570	.15	.3	.5	35	79	40
Potato, Sweet	32	31	10	243			.7			47
Beet, Greens	119	106	(130)	570			3.3			40
Lettuce	68	(11)	9	264	(.03)	.2	1.4		53	25
Spinach	93	88	71	470			3.1			51
Mustard Greens	183	27	32	377	.12		3.0	170	89	50
Kale	179	37	75	378			2.2			73
Tomato	13	14	3	244			.5			27
Strawberry	21	12	1	164			1.0			21
Onion	27	12	10	157			.5			36
Cucumber	25	11	6	160			1.1			27
Broccoli	103	24	15	382			1.1			78
Sugar Beets										

[1]Obtained from Watt and Merril (1963) and Paul and Southgate (1978).

[2]Estimated values.

Table 3a

COMPOSITION OF SELECTED PLANT SPECIES[1]

General

(per serving)

Species No.	Calories	Prot (g)	Fat (g)	Ash (g)	CHO (g)	Fiber (g)	Serving Size	Cooking Method
Soybean	117	9.9	5.2	1.4	9.7	2.3	1/2 cup = 90g	boiled
Dry Bean	106	7.0	.5	1.3	19.1	1.3	1/2 cup = 95g	boiled
Split Pea	118	9.3	.4	1.1	24	.5	1/2 cup = 100g	boiled
Podded Pea	(50)[2]	(3)	(.2)	(1)	(13)	(1.3)	(1/2 cup)	boiled
Chickpea	(113)	(9)	(2)	(1)	(24)	(2)	(1/2 cup)	boiled
Peanut	154	7.3	11.9	.7	6.4	.6	27g	roasted
Rice	116	2.5	.6	.4	25	.2	1/2 cup = 98g	boiled
Wheat	114	4.2	.5	(.6)	24	.8	1/2 cup = 68g	parboiled bulgur
Oats	66	2.4	1.2	.3	12	.2	1/2 cup = 120g	boiled oatmeal
Corn	68	1.7	.6	.2	14	.2	1/3 cup = 55g	whole grain boiled
Potato	84	2.0	.1	1.2	19	.4	1 tuber = 101g	boiled
Sweet Potato	252	3.7	1.4	2.3	57	2.1	1 = 205g	boiled
Beet Greens	13	1.3	.2	(1.0)	2.4	0.7	1/2 cup = 73g	boiled
Lettuce	8	.6	.1	.5	1.5	.3	2 lg. or 4 sm. leaves = 50g	raw
Spinach	21	2.5	.5	1.5	2.9	.8	1 cup = 80g	boiled
Mustard Greens	15	1.6	.2	.8	2.8	.6	1/2 cup = 70g	boiled
Kale	15	1.6	.2	.8	2.8	.6	1/2 cup = 70g	boiled
Tomato	30	1.5	.5	.9	6.0	.9	1 med = 150g	raw
Strawberry	55	1.2	.8	.8	12.1	2.1	1 cup = 149g	raw
Onion	19	.5	.1	.3	4.4	.4	50g	boiled
Cucumber	6	.4	.1	.2	1.4	.3	50g	raw
Broccoli	15	1.7	.1	.6	2.8	.7	1 cup = 150g	boiled
Sugar Beet								

[1]Proximate analysis obtained from Adams (1975). [2]Estimated values.

Table 3b

COMPOSITION OF SELECTED PLANT SPECIES[1]

Vitamins

(per serving)

	A IU	B_1 mg	B_2 mg	Nia mg	B_6 mg	Fd. µg	Pan. mg	Bio µg	C mg	E mg	Car. µg	Serving
Soybean	25	.2	.08	0.6							(50)	1/2 cup = 90g
Dry Bean	0	.14	.07	.7								1/2 cup = 85g
Split Pea	40	.15	.04	.9								1/2 cup = 100g
Podded Pea	(500)[2]	(.2)	(.07)	(1.6)								1/2 cup
Chickpea	50	.31	.15	2.0		37					210	1/2 cup = 100g
Peanut		.23	.19	12.4	.3		1.4			22		1/2 cup = 72g
Rice	0	.09	.04	2.7	(.05)	(6)	(.2)	(1.0)		(.1)		1/2 cup = 83g
Wheat	0	.33	.07	2.6								1/2 cup = 60g
Oats	0	.10	.03	.1								1/2 cup = 120g
Corn	200	.12	.04	.8	.09	18	.21			.3	13	1/2 cup = 58g
Potato	tr.	.12	.05	2.0	.18	10	.20		22	.1		1 = 150g
Sweet Potato	11940	.14	.09	.9					26			1 = 180g
Beet Greens	3700	.05	.11	.2					11			1/2 cup = 73g
Lettuce	1050	.03	.04	.2					10			55g
Spinach	7300	.07	.13	.5					25			1/2 cup = 90g
Mustard Greens	4060	.06	.10	.4					34			1/2 cup = 70g
Kale	4600	.06	.10	.9					51			1/2 cup = 55g
Tomato	410	.05	.04	.6					21			1 = 100g
Strawberry	90	.04	.10	.9					88			1 cup = 149g
Onion	40	.03	.03	.2					8			1/2 cup = 105g
Cucumber	130	.02	.02	.1					6			1/2 cup = 53g
Broccoli	3500	.13	.28	1.1					126			1 stalk = 140g
Sugar Beet												

[1]Obtained from Adams (1975).

[2]Estimated value.

Table 4

DAILY LIFE SUPPORT REQUIREMENTS

Type of Input	Amounts (kg/person/day) Gitel'son 1975	Modell 1977	Ward and Miller 1966
Food (dry)	0.6		0.52
Oxygen	0.9		0.86
Drinking water	1.8	2.2-2.5	2.2
Sanitary water	2.3	6.5	
Domestic water	16.8		

Table 5

A COMPARISON OF NUTRITION LEVELS IN FIELD AND PHYTOTRON GROWN RADISHES[1]

	Field	Phytotron
total amino acid content (%)	8.67	9.50
essential amino acid content (%)	3.56	3.61
mineral content (% dry matter)	7.89	8.25
ascorbic acid (mgm %)	21.4	37.6

[1]Obtained from Gitel'son 1975.

lar to that of plants grown in field environments.

Thus far, there have been few growth studies of higher plants conducted within spacecraft. The United States biosatellite experiments studied the effects of zero gravity on wheat seedlings and pepper plants over several days (Johnson and Tibbitts 1968; Lyon 1968). Russian studies in space have concentrated upon study of effects of radiation on plants. Some chromosomal abberrations have been found (Glembotskiy et al. 1962; Nikolayev et al. 1964). It should be noted, however, that the Apollo-Soyuz spacecraft carried Arabidopsis, Nicotiana and Zea but no significant differences were found between space grown plants and ground based plants (Anderson et al. 1979). Results indicated that plants tolerate radiation levels through processes of photo-adaption and repair injuries by photoactivation (Shakov et al. 1962) or may be protected by prior chemical treatment (Shaykarov 1965). The United States Space Science Board (1969) has concluded that there should be no significant radiation shielding problems in future space ventures. Therefore, radiation effects will not be considered further in this report.

There also is concern about the possible accumulation of toxins within a regenerative life support system, which might damage or kill plants or perhaps harm humans. Potential contaminants may be carried in the air, root medium or water. They may originate from man, the spacecraft, or the plants themselves. Plants are known to give off at least 200 discrete substances including hydrocarbons, aldehydes, alcohols, ketones, ethers (Gitel'son et al. 1975), carbon monoxide (Wilks 1959), various organic acids, amino acids, lactones, flavones (Dadykin 1968) as well as ethylene and terpenes that may be injurious and/or prevent normal plant growth (Ormrod 1979). Humans also release 150 volatile substances that may concentrate in a closed system and disrupt plant growth (Gitel'son et al. 1975). Plants such as beets give off

substances which might be harmful to other plants and even to the plant producing the substances (Milov et al. 1975). The significance of plant toxins was demonstrated in the BIOS III project conducted in the Soviet Union (Gitel'son et al. 1975). BIOS III was a six month, multiorganism study involving man, higher plants and algae systems. It was shown that higher plants grew vigorously without the algae system, but the plants died shortly after the algae were introduced into the unit. Presumably, unknown toxins given off by the algae killed the plants. Some chemicals given off by plants may accumulate within a regenerative life support system and be toxic to man. For example, radishes, tomatoes, carrots, and potatoes give off propionaldehyde which is toxic to humans (Rusakova et al. 1975).

Care should be taken to insure that seed stock and culture systems are reasonably free of pathogenic organisms. There is no evidence that a totally disease-free environment would be necessary or reasonable for effective plant growth in a closed system. Plants growing vigorously in controlled environments rarely develop disease problems unless pathogens are introduced by some external source.

Precise control of environmental conditions will be necessary to obtain maximum crop yields within a regenerative life support system. Assuming the availability of nuclear or solar energy (Miller and Ward 1966) space systems should not be constrained by energy availability. Therefore, continuous high irradiance lighting may be available. A few studies have demonstrated that plant growth is most rapid with continuous light of moderately high intensity (greater than 300 $\mu E\ m^{-2} sec^{-1}$) (Dolon 1973; Rao Rama Rao 1965). However, most plants have been found to have better growth with alternating light and dark periods that provide maximum yields with 16-18 hour light and 6-8 hour dark (Evans 1969; Gitel'son et al. 1975; Kristoffersen 1963).

Russian scientists have proposed that the light level for effective use of

plants in a regenerative life support system should be at least 50-60 Wm^{-2} PPFD (175-200 $\mu E\ sec^{-1}m^{-2}$ PPFD or 10-12 klux) (Gitel'son _et al_. 1975). However, it should be recognized that the rate of dry matter accumulation by most plants will increase with increasing light levels to 150 Wm^{-2} and higher for certain species (Warrington _et al_. 1978).

The spacing of plants within a growing system is critical for maximum yield. It has been established that the optimum leaf area index (vertical density of leaves) for planting varies depending on light intensity and quality of light. For instance, it has been estimated that a leaf index of 7-8 would be required for maximum yield when the level of radiation is 150 Wm^{-2} PPFD (Dadykin 1968).

One of the significant problems of plant growth in a controlled environment system is the selection of an appropriate rooting medium that will afford optimum nutrition and yet be practical in terms of total amount of salt and water required. Previous experiments proposed for space systems have detailed a variety of techniques, including liquid culture (Krauss 1962), aeroponics (Dadykin 1968; Milov _et al_. 1975), artificial nutrient media such as vermiculite (Anonymous 1965; Lebedeva 1964) and perlite (Milov _et al_. 1975). Other methods under study include the nutrient film technique (Dadykin 1968) and subirrigation air cultivation which has been used to successfully cultivate grain crops within regenerative life support systems (Gitel'son _et al_. 1975). The use of aeroponics and subirrigation air cultivation techniques can minimize significantly the total weight of the plant-culture system. However, these systems require frequent and regular care to maintain desirable salt balance and solution pH. Growth in artificial media also can result in the uptake of undesirable chemicals into plants. Problems have been reported for many different media. For example, it has been reported that plants can take up high level of fluorides if grown in perlite (Ormrod 1979).

II. CRITERIA FOR PLANT SELECTION

A. Food Production

Species and cultivars should be selected that produce the maximum quantity of digestible biomass and the minimum quantity of non-digestible biomass based on an integration of the following unit factors:

a. volume of space required per unit time

b. labor requirements

c. weight of the plant-growing system

d. electrical energy utilized

e. purchase and maintenance costs of plant-growing system

Integration of these factors for each plant species will require determining the magnitude of each of these unit factors. Therefore, a primary requirement for the plant research for life support systems will be in determining these unit factors and developing mechanisms for minimizing their impact.

B. Nutrition

Plants grown in the CELSS must be able to provide a nutritionally and psychologically satisfactory diet for the human inhabitants. The selected plant species must be evaluated in terms of a number of "use" criteria, including: energy concentration, nutritional composition, palatability, processing requirement, acceptable serving size and frequency, flexibility of usage, storage stability, toxicity, degree of human nutritional experience. A group of plant species should be selected that will provide balanced nutrition at levels sufficient to cover requirements for humans. However, to obtain maximum efficiency, the possibility of supplementing the diet with animal protein, and certain prepared minerals and vitamins should be included in diet development. The efficiency of different plant species should be compared on the basis of the quantity of food that is digested by humans.

It is possible for an adult person to obtain sufficient energy on a strict vegetarian ("vegan") diet. The amount of energy required is related to age and weight (Table 6), sex, degree of physical activity, including physical and psychological stress, and environmental conditions. For an average adult diet of 2300 calories, about 400 grams of carbohydrates per day should be included (Wilks 1964). The U.S. Dietary Goals suggests that the distribution of energy sources for the general public as 58% from carbohydrates, 12% from protein, and 30% from fat. A somewhat higher energy contribution from protein is recommended under stressfull conditions (Gemini and Appollo projects, Table 7). Sugar usage should be limited to adding culinary interest and/or to increase energy intake whenever this is difficult through other means.

Protein is of major concern in a vegetarian diet both for energy and to supply needed amino acids for the body. Plant proteins occur generally at low concentration, except in legume seed and nuts and their quality is generally poor. Protein, from different plants, vary in the type and proportion of amino acids. Ideally, amino acids should be absorbed from the digestive tract of humans in proportions similar to their occurence in the tissues that are being replaced. The amino acid composition of individual plant proteins are compared to that of the human body or whole egg protein, which often is taken as a reference protein (Table 8). It is generally found that most plant proteins are not fully utilized in the intestinal tract. The digestibility coefficient varies from 20% for sorghum to 89% for certain wheat flours. Most plant proteins have a digestibility coefficient fairly close to 75%. When a meal is composed of proteins from several sources and has a total composition more closely resembling the requirements of essential amino acids (Table 9), it is found that the digestibility is also improved. The diet should contain between 50-100 grams of protein (Table 1).

Table 6

CALORIC REQUIREMENT OF ADULT MALES PER DAY[1] (Normal activity)

Body Wt.		Kilocalories at Age:		
kg.	(lb)	25	45	65
50	110	2300	2050	1750
60	132	2600	2350	1950
70	154	2900	2600	2200
80	176	3200	2900	2450

[1]Adapted from Consolazio (1964).

Table 7

CALORIE INTAKE PATTERNS OF DAILY DIETS[1]

			Space Programs		
Food Constituent	U.S. Current Practice	U.S. Dietary Goal	Project Gemini (2500 kcal)	Project Apollo (2800 kcal)	Nikishanova
			(Percentage)		
Carbohydrates	46	58	51	51	60-65
Protein	12	12	17	17	10-15
Fat	42	30	32	32	20-25

[1]Obtained from Klicka et al. 1967, and U.S. Senate 1977.

Table 8

RELATIVE PERCENTAGE OF ESSENTIAL AMINO ACIDS OF SOME PLANT PROTEINS COMPARED TO AMINO ACIDS OF EGG PROTEIN[1]

	Foodstuffs				
Amino Acids	Soybean meal, low fat	Whole Rice	Whole Wheat	Peanut Flour	Dried Roast Beans
Histidine[2]	128	81	100	100	104
Threonine	80	78	67	57	79
Valine	76	88	62	66	78
Leucine	89	91	78	79	78
Isoleucine	97	84	64	66	89
Lysine	111	52	44	57	106
Methionine	53	106	78	25	62
Phenyalanine	95	89	91	88	89
Tryptophan	127	118	109	72	73

[1]Calculated from FAO (1970a).

[2]Not generally considered essential for adults.

Table 9

ESTIMATED ESSENTIAL AMINO ACID REQUIREMENTS OF ADULTS[a]

Essential Amino Acid	Men (mg/day)	Women (mg/day)
Histidine	700	450
Isoleucine	1100	620
Leucine	800	500
Methionine -		
in absence of cystine	1100	550
in presence of 810 mg cystine	200	(180)
Phenylalanine -		
in absence of tyrosine	1100	
in presence of 1100 mg tyrosine	300	(200)
Threonine	500	300
Tryptophan	250	160
Valine	800	650

[a]These estimates emphasize the upper range of individual requirements adapted from FAO (1973).

Lipids form an important part of the diet as a source of energy and for culinary reasons. Fats and oils are needed for cooking oils, spreads, dressings and flavorings. The lipid intake should not exceed 35% of the total energy supply. A daily consumption of approximately 60 grams is adequate for a person on a 2300 calorie diet (Wilks 1964).

Sufficient amounts of most vitamins and minerals can be supplied from plant sources. However, it is difficult to get sufficient riboflavin from plants, and vitamin B_{12} does not occur in the plant kingdom. Among the minerals and trace elements, iodine may occur at suboptimal concentrations, and the low bioavailability of calcium, iron, zinc, and copper may render these deficient although they may nominally be present in sufficient amounts. Supplementation may be considered for these minor nutrients.

A 14-day cycle pure vegetarian menu was analyzed as a base to explore problem areas (Table 1). Dietary deficiencies for energy, protein, iron, vitamin B_{12}, and riboflavin are evident. A compilation of nutritional compositional data of ten different plant species is listed in Table 10. It further illustrates the difficulty of supplying sufficient energy intake while maintaining a balanced intake of nutrients. With implementation of modifications and further experimentation it can probably be developed into a satisfactory menu. The species diversity in this listing also recognizes the importance of some of the criteria mentioned earlier.

C. Oxygen Production and Carbon Dioxide Utilization

As actively-growing plants photosynthesize, carbon dioxide is fixed into organic carbon and oxygen is released. This oxygen can be utilized for human respiration if the atmosphere of the plant growing area is effectively integrated with the human habitation areas of the spacecraft. Plants can also help in maintenance of carbon dioxide levels in a regenerative life support

Table 10

Balanced Daily Diet Developed from Plant Sources[1]

Plant Species	Quantity: Serving No.	Quantity: Raw or Fresh Weight (g)	General Composition: Cal.	General Composition: Pro. (g)	General Composition: Fat (g)	General Composition: CHO (g)	Minerals: Ca (mg)	Minerals: Na (mg)	Minerals: Fe (mg)	Vitamins: A (IU)	Vitamins: B_1 (mg)	Vitamins: B_2 (mg)	Vitamins: Nia (mg)	Vitamins: C (mg)
Soybean	4	360	468	39.5	20.8	38.8	245	5.4	9.1	27	.22	.09	.65	--
Split Pea	2	200	236	18.6	.8	48.0	99	26.0	3.7	80	.30	.08	1.80	--
Chick Pea	2	200(est)	226	18.0	4.0	48.0	88	25.0	4.0	32	.18	.10	1.24	--
Peanut	2	54	308	14.6	23.8	12.8	66	6.4	2.2	--	.12	.10	6.70	--
Rice	4	392	464	10.0	2.4	100.0	41	11.6	2.1	--	.36	.16	10.80	--
Wheat	4	272	456	16.8	2.0	96.0	50	4.1	4.3	--	1.32	.28	8.40	--
Corn	2	110	136	3.4	1.2	28.0	9	.4	.8	400	.24	.08	1.60	--
Sweet Potato	1	205	252	3.7	1.4	57.0	80	25.2	1.8	11,940	.14	.09	.09	26
Mustard Greens	1	70	15	1.6	.2	2.8	92	16.0	1.5	4,060	.06	.10	.40	34
Strawberry	1	149	55	1.2	.8	12.1	31	2.0	1.5	90	.04	.10	.90	88
TOTALS	23		2,615	127.5	57.4	443.5	801	122.1	31.0	16,629	2.98	1.18	33.39	148
% of RDA			97	288				~10	301-172	333	212	73	186	246

Total Volume: ~2.7L ÷ 4 = 675 ml per meal

Energy distribution: CHO: 67.8%, Protein: 19.5%; Fat 20.8%

[1]Calculated from Adams (1975).

system. Carbon dioxide exhaled by humans in the spacecraft can be cycled to the plant growing area and assimilated into organic matter by the plants. However, it should be recognized that the CO_2 incorporation and the O_2 production by a growing crop will not necessarily represent the effective gas exchange in a regenerative life support system. Only exchange associated with digestible food obtained from each plant is useful. The oxygen that must be consumed during plant decomposition of this non-digestible fraction is equal in quantity to the oxygen released in the photosynthetic production of that fraction. Also, not until non-digestible plant parts have been decomposed (oxidized) to CO_2 and water will the life support system be truly regenerative. Therefore, plant species should preferably be selected to provide maximum edible and minimum non-edible biomass.

There is considerable variation among plants in their ability to produce oxygen but it is in direct proportion to the rate of net photosynthesis at any particular time. Thus, oxygen evolution can be assumed to be approximately proportioned to dry matter accumulation. The oxygen production in liters/m^2/day is numerically equal to dry mass production in g/m^2/day when the dry mass consists of sugars. This equity was utilized by Milov and Balakireva (1975) for estimating O_2 production from dry mass production.

It was found that 10 m^2 of plant growing area provided adequate oxygen for one person in a six months closed life support experiment (Gitel'son 1976). The minimum surface area required will vary according to the plant species being grown and the extent of surface area that can be continuously covered with photosynthesis tissue. Oxygen production and CO_2 incorporation by plants in the system could be balanced against human activity patterns in various way such as by:

1) Providing multiple plant growth compartment chambers so that a portion of the plant population would be photosynthesizing, while other portions are in darkness.

2) Altering radiation or temperature levels to moderate photosynthetic rates as needed.

3) Providing a system of gas storage.

Since maximum oxygen production and carbon dioxide utilization generally occurs during periods of maximum plant growth, frequent planting and harvesting will be required to assure desired gas exchange.

D. Water Recycling

Higher plants give off predictable quantities of water as transpiration, at rates that are considerably greater during light than during dark. The transpired water vapor can be used to maintain humidity in the plant growing areas or directed to other compartments of the spacecraft for humidity maintenance. Some of the water vapor may be condensed for use as potable water.

The rate of water release from plants can be controlled in several different ways to satisfy moisture and water demands within the spacecraft. Controls include varying the humidity level of the plant growing area, varying the intensity and length of the light period and amount of plant surface maintained.

It has been suggested (but not proven) that plants give off harmful substances, such as alkaloids, with the transpired water (Derendyayeva 1973) and thus water condensed from the air may need further purification before being used for drinking or in support of growth of other plants.

E. Waste Recyling

The possible use of higher plants for recycling human wastes within a regenerative life support system appears feasible (Berry *et al*. 1977; Furr *et al*. 1976);

Gordon 1978; Wallace et al. 1976). Lettuce has been successfully cultured on activated sludge after appropriate mineralization by microorganisms (Drake 1966). However, some problems have been encountered when Chinese cabbage, tampala and endive were cultured on activated sludge because certain nutritive elements were unavailable (Drake 1966). Russian studies (Tsvetkova et al. 1965) have shown that such problems can be overcome by proper mineral supplementation of the activated sludge.

F. Other Criteria

Plant species (and cultivars) should be selected with consideration for the following desirable, but not necessarily essential, morphological and physiological characteristics:

1) Short plants with high leaf density are desirable to maximize space utilization and light interception per unit volume.
2) Growth habit, determinate or indeterminate, for most efficient production over time.
3) Species and cultivars with a wide range of environmental tolerance should be selected for maximum flexibility in multiplant systems and tolerance to uncontrolled environmental extremes. This would include tolerance to a wide range of radiation, temperature, humidity, media moisture, nutrient, salt and pH levels.
4) Plants that accumulate or release toxic compounds into the atmosphere. On the other hand, species that effectively remove toxic compounds from the media or atmosphere should be utilized, providing the plant tissues do not accumulate any toxic components.
5) Species and cultivars should be selected that have maximum disease resistance in combination with high productivity.
6) Plants that produce irritating air borne pollen should not be utilized.
7) Self pollinating species are preferred to avoid problems of seedset.

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IV. RECOMMENDATIONS

A. Plant Species

Plant species for the regenerative life support systems were identified that would meet both the major nutritional needs of man and also represent uniquely different growth morphologies for system development. These species were designated as reference plants, representative of related species that might be utilized in an operational life support system.

Two groups of plants were selected for research study. The first group of eight plant species was designated for intensive study and are species that are commonly utilized food plants and could provide the major nutritional needs of man. Intensive research efforts should be undertaken to establish their baseline and optimum productivity in life support systems as detailed in the research priorities of Section C of these Recommendations.

The second group of six plant species was designated for exploratory study and were species for which there is less reported information or that have lower nutritive values but high psychological value. Research should be undertaken, and principally limited to,establishing their baseline productivity in a life support system and to developing culture procedures for possible use in a regenerative life support system.

It is intended that study of these two groups will provide the necessary information to develop an effective operational system for these or other food crops having similar or related growth requirements.

Reference Plants: Intensive Study

Wheat - Wheat was selected because of its high caloric density and because it is the basis for many different types of foods that can be produced with minimum processing. The edible proportion of the total biomass is high. Wheat

contains a high starch content, contains a reasonable amount of protein (to 14%), as well as phosphorus, iron, thiamin, niacin and fiber. It is recommended that dwarf cultivars be utilized. Use of wheat will be limited by the fact that photosynthesis ceases during seed maturation. Spring wheat cultivars should be selected in preference to winter wheat to avoid a requirement for vernalization.

Rice - Rice, as wheat, was selected for its high caloric density. It supplies slightly less protein (8%) but has a more nutritionally balanced protein than does wheat. Rice also supplies phosphorus, iron, thiamin and niacin. Research should be undertaken to determine if strains can be maintained in an indeterminate growth habit to increase productivity.

White Potatoes - White potatoes were selected because they are a high calorie food that can provide a wide variety of useful foodstuffs for man with minimum processing. The carbohydrate is not as dense as that of wheat and the protein concentration on a dry weight basis is similar to that of rice. White potatoes also provide a good source of vitamin C and potassium. In liquid or mist culture, tuber production will require unique mechanical systems for support. Researchers should explore the possibility of obtaining indeterminate growth habit of plants by early and frequent harvesting of the tubers to increase productivity.

Sweet Potato - Sweet potatoes have been selected because they are adapted to warm environments and also are a high calorie food. The food can be eaten with very little processing. The carbohydrate is about 30% more dense than that of white potatoes and the protein concentration is similar to that of white potatoes. Sweet potatoes provide potassium, vitamin A and vitamin C.

The leaves and young shoots of sweet potatoes are edible and may have limited use in the diet. Sweet potatoes also will require the development of unique mechanical support systems for the enlarged roots in liquid and mist culture systems. The vigorous vine-type growth of the stems may be a disadvantage for use of this species.

Soybeans - Soybeans were selected because they can serve as a major source of dietary protein. The seeds have greater concentrations of protein (45-50%) than any other common plant food. The essential amino acids are well balanced except that methonine tends to be low. The protein is highly digestible and has a wide range of utilization in the diet. There also is a significant amount of oil in soybeans that would be available for food preparation and other uses, but the oil must be processed before it can be used. Soybeans are a good source of phosphorus, iron, potassium and thiamin.

Soybeans have a reasonably well defined morphology that should permit efficient and easily manipulated growth in a space system. The inclusion of soybeans provides a plant type that is representative of other legumes that might be utilized in a life support system.

Peanuts - Peanuts also were selected as a major source of protein for the diet. The seeds contain about 25% protein. The essential amino acids are not as well balanced as in soybeans and methonine also tends to be low. The oil concentration is about 45%, or about twice that in soybeans. The oil can be expressed and utilized directly without processing. The seeds are another good source of phosphorus, iron, potassium, thiamin and niacin.

The growth habit of peanuts, involving seed production below the soil surface, may result in excessively complicated growing and harvesting procedures.

Lettuce - Lettuce was selected to provide a salad crop for variety in the diet. It provides significant quantities of vitamin A and C. It is a low growing crop with defined shape that has been cultivated extensively in controlled environments. Leaf, rather than heading types, are recommended to minimize production problems and permit multiple harvests from the same plants.

Sugar beets - Sugar beets were selected to provide sugar, both for the diet, and for possible culture of single-cell organisms as a secondary food source. Sugar

beets have a plant type that is representative of most other root crop species that might be utilized in a life support system as red beets, radishes, carrots, turnips and rutabagas. The beets can be eaten raw and the tops also are edible and may have use in the diet. The weight penalty for equipment to extract sugar from beets should be carefully determined.

Reference Plants: Exploratory Study

Taro - Taro was selected as a representative tropical root crop. Taro and other root crops (e.g. manioc) are utilized infrequently for food in temperate regions of the world. Investigations should be undertaken to determine if the yield of edible portion of this crop is comparable to that of white potatoes and sweet potatoes. The tops also might be utilized for food.

Winged beans - Winged beans were recommended for study because this species is under intensive study as a food source in many areas of the world. It is recognized as a good protein source, and both tops and roots can be eaten. It is adapted to warm temperatures, although additional study is needed to determine its edible productivity and acceptability as a food along with study of its growth under controlled environment conditions.

Broccoli - Broccoli was selected because it provides a rich source of vitamins A, B_1 (thiamin), B_2 (riboflavin), B_7 (niacin) and C. Broccoli has a growth habit similar to other Cruciferae (cabbage, kohlrabi, cauliflower, Chinese cabbage and Brussels sprouts), that might be utilized in a life support system. The green broccoli is recommended for study.

Strawberries - Strawberries were selected to include a fruit crop that would provide additional variety to the diet. The psychological value of this pleasing food may be very great in a life support system. Strawberries would provide large amounts of vitamins B_2, B_7 and C to the diet. As strawberries are low growing and can be maintained as single plants without runners, they could be

grown efficiently and manipulated easily in a space system. Day neutral varieties with continuous production would be preferable. There is a need to optimize production for strawberries in hydroponic culture.

Onions - Onions were selected to provide a commonly used source of seasoning for many foods. They provide no significant nutritional value to the diet. The growth habit of this plant will require different systems for support because there is neither a tap root (only a fibrous root), nor significant stem formation (only a bulb developing from fleshy leaf blades). Day neutral cultivars should be selected to insure bulb enlargement under long days.

Peas - Peas are included because dried peas are a rich protein source similar to that of peanuts and provide high amounts of methonine, which is low in soybeans and peanuts. Peas contain little fat, but contain relatively large quantities of minerals such as potassium, copper, iron, sulfur and phosphorus. Peas do not have a strong stem, so culture systems will have to be developed for effective shoot support for these plants. It may be possible to use cultivars having edible pods, but their harvestable seeds have lower nutritional value and lower productivity than conventional dried pea cultivars.

B. Growing Procedures

The following recommendations are intended as guidelines to indicate the environmental and cultural considerations that should be controlled and stuied in the plant research. It is anticipated that these guidelines will be periodically updated as requirements for individual species are elucidated and new technology becomes available. The development of comprehensive quality assurance programs to detail seed handling procedures, replication, environmental measurement and calibration, data collection and statistical analysis should be undertaken during the first years of this program so that research undertaken in different laboratories can be compared effectively.

Temperatures - No particular guideline temperatures are proposed at this stage in the study of higher plants for regenerative life support systems. Temperature optima at different stages of development for each species must be established. Day-night temperature differentials should be studied to determine their optima under different radiation and humidity levels. Leaf temperatures should be measured so as to provide an accurate basis for air temperature control, especially when establishing effective radiation levels. Also, media or root temperatures should be monitored and possibly controlled separately from air temperatures to optimize growth of the plants.

Radiation - The radiation guideline is at least 325 $\mu E\ m^{-2} sec^{-1}$ photosynthetic photon flux density (PPFD) in order that plant morphology and rates of growth at least approximate those of field growth of plants. The effects of radiation levels in excess of this level also should be explored for each species.

A 325-450 $\mu E\ m^{-2} sec^{-1}$ level of radiation can be provided with 1500 ma fluorescent lamp (typically cool-white) supplemented with incandescent lamps in most standard reach-in and walk-in chambers. Levels to 600 $\mu E\ m^{-2} sec^{-1}$ can be obtained with well constructed walk-in chambers. Higher levels of radiation will require the use of high intensity discharge (HID) lamps. Particular lamp types for high radiation levels need additional study, but phosphor coated metal-halide lamps alone or in combination with sodium lamps appear best for general high radiation level applications.

The use of long photoperiods of 18, 20 or 24 hour would permit irradiation with lower levels than if shorter photoperiods were utilized. The radiation provided to plants should be expressed as quantum-per-day to simplify comparison of radiation levels in studies.

Carbon dioxide - There is a need for continuous monitoring of carbon dioxide levels during growth rate investigations with plants because both the large increases in carbon dioxide when humans are present in the growth area and depletion when

there is a large photosynthetic surface, may greatly affect photosynthetic rates. Carbon dioxide control should be provided in chambers, where possible, with flexibility to control levels between 350 and 2000 ppm.

Atmospheric moisture - The need for humidity control in growth rate investigations with each plant species also is recognized. A relative humidity level of 70% is encouraged for general use at temperatures between 15 and 30°C during both the light and dark periods. It is recognized that this set RH level will provide different vapor pressure deficits at different temperatures, but this specific humidity level is encouraged until the requirements for particular species can be established more precisely.

Media - It was agreed that plant investigations involving productivity and nutrient interactions should be undertaken using hydroponic culture so that accurate knowledge of nutrient concentrations is obtained and the studies can be effectively duplicated. The hydroponic culture could involve use of liquid culture, liquid film technique, mist culture, or use of inert gravel or sand as supporting media.

Investigations involving aspects other than productivity and nutrient interactions, may be undertaken in peat-vermiculite or other solid media to simplify growing procedures providing growth rates and plant type in solid media are similar to those obtained in hydroponic culture.

pH and Conductivity - Solution pH must be audited regularly, and the pH adjusted at least once daily, or more frequently if containers and solution reservoirs are of small volume. The use of automatic pH controllers is recommended. The pH of the solution should be maintained within the range of 4-6.5 pH units. The conductivity of the solution should be monitored in order that a level is maintain that is between 1/2 and 2x the initial solution conductivity.

Seed Germination - Germination procedures must be developed for individual crop species to provide seedlings with enough elongation of the main axis to be effectively supported in hydroponic culture.

Plant Spacing - Optimum plant spacing must be determined from seeding to final harvest for each species. The spacing should be gradually increased with increasing plant size to assure maximum utilization of space. Optimum spacing will vary markedly among species as well as among cultivars.

Interval Between Plantings - The optimum interval between plantings to maintain a continuous food and oxygen supply will be determined separately for each species. It will be controlled by the length of the harvesting period, the length of storage period for the harvested crops, and the amount of photosynthesizing crop canopy needed at particular times to supply human O_2 requirements.

Length of Production Cycle - The length of the production cycle will vary for each crop species and for particular cultivars within a species.

Insect and Disease Control - A minimum amount of pesticide applications are recommended for insect and disease control. This is desirable to reduce the possibility of plant growth reductions as well as human toxicity from the applied pesticides. Construction of multiple plant compartments will minimize risk from insects and diseases. Plant growth compartments should be programmed to allow for short empty periods at intervals to aid in eradication of any possible insects and diseases before they can increase to serious levels. It is recommended that procedures be instituted to minimize the incidence of insects or diseases on seeds and other supplies at the initiation of each study. This will greatly reduce the risk of serious infestations.

Seed Maintenance and Storage - A supply of seed of each selected cultivar should be obtained from a primary producer so that the lot is known and additional seed can be obtained in the future from the same foundation stock. Seed should be

obtained and maintained at a location from which all scientists undertaking studies with a given species can utilize seed from the same stock. Seed should be sized to eliminate large and small seeds, and thus have a seed lot with maximum uniformity. Seed also should be carefully stored under the proper conditions of humidity and temperature so as to maintain maximum viability. The seed lot should be monitored for germination and vigor periodically. Small samples should be distributed in moisture proof containers for use in different laboratories with instructions on handling and storage.

C. Research Priorities

Research priorities have been divided into primary needs, secondary needs, and development needs. Primary needs are those factors required to provide a basis for utilizing, and determining the trade offs for use of higher plants in a regenerative life support system. Primary needs provide a basis for the functioning of other programs in the regenerative life support project; human requirements, waste management, and systems development. Secondary needs are those that are developed either from information generated from primary needs research or those required when the life support system is being integrated, i.e., growth of mixed species, recirculation of nutrients, utilization of waste from reference plants etc. Funding of secondary needs should be delayed 3-5 years after initiating funding of primary needs. Development needs involve primarily research that would increase the reliability of higher plant use in a regenerative life support system. These needs should be funded when there is agency committment for the construction of regenerative life support systems for space use. Limited research might be undertaken in these areas earlier but should not preempt research efforts directed toward the primary and secondary needs that are outlined.

Primary Needs:

1) Develop a quality assurance program for the plant research. This should include:

   a) seed maintenance and distribution

   b) experimental design and replication

   c) environmental measurement and control and instrument calibration

   d) plant growth data collection and statistical analysis.

2) Establish and optimize the efficiency of production of digestible food, oxygen production and water recycling by reference plants on the basis of: volume and area of space required per unit time; labor requirements; weight of the plant growing system; electrical energy utilized; and purchase and maintenance costs of plant growing system. The research efforts should involve:

   a) photosynthetically active radiation (PPFD) level, spectral balance and duration

   b) light and dark temperature levels, shoot and root temperature differentials, temperature optima at different stages of growth

   c) humidity levels during light and darkness

   d) carbon dioxide concentration

   e) nutrient balance and concentrations at different rates of growth and stages of maturity

   f) watering procedures, amount and frequency

   g) pH level and control

   h) plant spacing at different stages of growth

   i) selection of hydroponic culture method

   j) germination procedures

   k) plant support procedures

l) nutritional value of edible plant parts

m) cultivar selection

3) Establish nutrient and volatile gas toxicity for individual species in a recirculating system. This will include:

   a) heavy metal and volatile emissions from structural materials

   b) volatile plant emissions and root exudations

4) Determine utilization and tolerance of human and plant wastes by plants. This will include:

   a) direct and partially-decomposed waste

   b) nutrient composition and availability in wastes

   c) pH control in wastes

   d) elemental and organic toxicants in waste

   This research effort will require integration with microbiologists and engineers in the waste management program.

<u>Secondary Needs</u>:

1) Determine possible mutual toxicities between reference species when grown in the same system. This will include:

   a) volatile emissions

   b) exudations into nutrient media

   c) toxicities in decomposed waste

2) Collation of data accumulation from reference plants to provide a data base for systems integration.

<u>Development Needs</u>:

1) Determine range of environmental, including substrate, conditions for efficient food production, oxygen production and water regeneration for each reference species including radiation, temperature, humidity, carbon dioxide, nutrients and pH.

2) Screen available germplasm and develop improved cultivars for greater efficiency in regenerative life support systems.

3) Determine capacity of reference species for removal of atmospheric contaminants from the spacecraft atmospheres.

4) Establish whether reference species can be grown effectively in low gravity environments.

5) Determine effectiveness of _in vitro_ culture procedures for propagation of reference species.

6) Investigate use of plant hormones and growth regulators to increase the efficiency of reference species in a regenerative life support system.

7) Automation of planting, spacing and harvesting.

V. BIBLIOGRAPHY AND PRODUCTIVITY OF THE SELECTED PLANT SPECIES

The literature has been reviewed to obtain published information on controlled environment growth of the selected species. The data obtained is quite incomplete for there is limited data from controlled environments for many species. Also, it has often been impossible to translate the published data into meaningful data for use in life support systems. For example, plants in controlled environment studies have been maintained commonly in individual containers and therefore, unless container spacing is reported, the data can not be translated to production per-unit-area. Accurate comparison of productivity among different studies is limited by the fact that some studies are initiated from seeding in controlled environments while other studies are begun with transplants.

Literature citations for research undertaken with each species are provided in the following pages. The citations have been obtained both from scientists working with each of these plant species and through literature searches using available computer data bases. Some citations cover field research results when the data seemed particularly appropriate for the application of plants to life support systems. Most of the listed citations have been reviewed and only conclusive and appropriate literature citations have been included. Some citations were included even though not reviewed when the title or abstract indicated that the research would likely have application for life support systems.

A summary table of the available production information is provided (Table 11). The large variation in productivity among studies is a result both of differences in environmental conditions and also because some production data was based on growth for the total period from seeding to harvest and other data for only the period from transplanting to harvest. It is

difficult to estimate maximum productivity values for any of these species from this presently available data.

Table 11

PRODUCTION IN CONTROLLED ENVIRONMENTS*

Plant Species	Reference		Location	Growing Period (Days)	Production: Edible Dry Weight*** ($g\ m^{-2}\ day^{-1}$)	Production: Oxygen $g\ m^{-2}\ day^{-1}$	Production: Water $kg\ m^{-2}\ day^{-1}$
Broccoli (*Brassica oleracia* var. *botrytis*)	(See below)**		Field	60 (Transplant)	1.31 (10.9)		
Lettuce (*Lactuca sativa*)	Milov & Novikova	1975	Growth Chamb	22 (Transplant)	13.6	33.1	1.1
	Hammer et. al.	1978	Growth Chamb	28 (Seeded)	6.0		
	Tibbitts & Kozlowski	1980	Growth Chamb	28 (Seeded)	8.6		
	Fontes	1973	Greenhouse	38 (Transplant)	8.3		
	(See below)**		Field	60 (Seeded)	2.06 (4.9)		
Onions (*Allium cepa*)	(See below)**		Field	110 (Seeded)	3.12 (10.9)		
Peanuts (*Arachis hypogaea*)	Milov & Novikova	1975	Growth Chamb	90 (No info)	8.9	18.0	3.0
	(See below)**		Field	120 (Seeded)	2.63 (94.4)		
Peas, Dry (*Pisum sativum*)	(See below)**		Field	100 (Seeded)	1.68 (88.3)		
Rice (*Oryza sativa*)	Int. Rice Inst.	1976	Greenhouse	110 (Transplant)	8.4		
	Ishizuka	1979	Field	110 (Transplant)	7.6		
	(See below)**		Field	110 (Transplant)	3.25 (88.0)		
Soybeans (*Glycine max*)	Milov & Novikova	1975	Growth Chamb	80 (Transplant)	1.7	5.6	3.5
	Patterson et. al.	1977	Growth Chamb	115 (Seeded)	4.8		
	Sionit & Kramer	1977	Growth Chamb	120 (Seeded)	2.2		
	Raper & Thomas	1978	Growth Chamb	148 (Seeded)	6.8		
	(See below)**		Field	120 (Seeded)	1.34 (90.0)		
Strawberries (*Fragaria x ananassa*)	(See below)**		Field	365 (Plants)	0.12 (10.1)		
Sugar beets (*Beta vulgaris*)	Milov & Novikova	1975	Growth Chamb	100 (No info)	32.4	62.6	2.0
	(See below)**		Field	140 (Seeded)	5.22 (13.0)		
Sweet Potatoes (*Ipomoea batatas*)	Milov & Novikova	1975	Growth Chamb	90 (No info)	13.0	34.6	2.7
	Huett	1975	Field	147 (Transplant)	20.3		
	Nikishanova	1977	Growth Chamb	150 (No info)	30.0		
	(See below)**		Field	120 (Transplant)	2.80 (29.4)		
Taro (*Colocasia esculenta*)	(See below)**		Field	270 (No info)	2.21 (27.0)		
Wheat (*Triticum sativum*)	Gitel'son	1975	Growth Chamb	75 (Seeded)	16.4		
	Gifford	1977	Greenhouse	130 (Seeded)	9.4		
	(See below)**		Field	100 (Seeded)	3.85 (87.0)		
White Potatoes (*Solanum tuberosum*)	Milov & Novikova	1975	Growth Chamb	80 (Transplant)	19.0	40.8	2.5
	McCown & Kass	1977	Growth Chamb	135 (Tubers)	14.4		
	Mendoza & Haynes	1976	Growth Chamb	120 (Tubers)	6.7		
	(See below)**		Field	120 (Tubers)	4.30 (20.2)		
Winged Beans (*Psophocarpus tetragonolobus*)	Nangju	1979	Field		1.1		

*Production from field environments is shown for comparison and when no controlled environment production was available for that species.

**Field production values determined from maximum yields published in agricultural statistics (USDA, 1979) and dry weights of produce reported in food handbook (USDA, 1975).

***Percent of fresh weight in parenthesis.

Literature Citations

Broccoli

Brassica oleracia var. botrytis

REFERENCE CITED		LOCATION			EXPERIMENT VARIABLES: Radiation			Temperature							Media						DATA OBTAINED: Production						Nutrition			Toxins	
		Growth Chambers	Greenhouse	Field	Level	Photoperiod	Spectrum	Air	Soil	Leaf	Carbon dioxide	Humidity	Spacing & Growth Proc.	Type	Nutrients	pH	Soil potential & water stress	Tissue culture	Chemical hormones	Tops	Roots	Edible	Oxygen (carbon dioxide uptake)	Water		Carbohydrates	Proteins	Other	Human	Plant
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Anderson	1976	X																X												
Anderson et. al.	1977	X																X												
Cutcliffe	1975			X									X									X								
Maurer	1976			X													X			X	X	X		X						
Palevitch & Pressman	1973			X									X									X								
Thompson & Taylor	1976			X									X									X								
Wiebe	1975	X						X												X		X								

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Literature Citations

Lettuce

<u>Lactuca sativa</u>

		LOCATION			EXPERIMENT VARIABLES															DATA OBTAINED										
					Radiation			Temperature						Media						Production						Nutrition			Toxin	
REFERENCE CITED		1 Growth Chambers	2 Greenhouse	3 Field	4 Level	5 Photoperiod	6 Spectrum	7 Air	8 Soil	9 Leaf	10 Carbon dioxide	11 Humidity	12 Spacing & Growth Proc.	13 Type	14 Nutrients	15 pH	16 Soil potential & water stress	17 Tissue culture	18 Chemical hormones	19 Tops	20 Roots	21 Edible	22 Oxygen (carbon dioxide uptake)	23 Water	24	25 Carbohydrates	26 Proteins	27 Other	28 Human	29 Plant
Bensink	1971	X				X														X										
Bierhuizen, et. al.	1973		X		X			X												X		X								
Enoch, et. al.	1970		X								X									X		X								
Fontes	1973		X																	X		X								
Hammer, et. al.	1978	X																		X		X								
Langhans	1978	X																					X							
Milov & Novikova	1975	X																		X		X	X	X						
Prince & Bartok	1978	X											X							X		X								
Read	1972	X			X						X	X								X		X								
Soffe et. al.	1977	X																		X		X								
Tibbitts & Bottenberg	1976	X																		X		X	X							
Wiebe & Lorenz	1977	X						X																						

Lettuce

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Literature Citations

Onions

<u>Allium cepa</u>

REFERENCE CITED		LOCATION: 1 Growth Chambers	LOCATION: 2 Greenhouse	LOCATION: 3 Field	EXPERIMENT VARIABLES — Radiation: 4 Level	Radiation: 5 Photoperiod	Radiation: 6 Spectrum	Temperature: 7 Air	Temperature: 8 Soil	Temperature: 9 Leaf	10 Carbon dioxide	11 Humidity	12 Spacing & Growth Proc.	Media: 13 Type	Media: 14 Nutrients	Media: 15 pH	Media: 16 Soil potential & water stress	17 Tissue culture	18 Chemical hormones	DATA OBTAINED — Production: 19 Tops	Production: 20 Roots	Production: 21 Edible	Production: 22 Oxygen (carbon dioxide uptake)	Production: 23 Water	Production: 24	Nutrition: 25 Carbohydrates	Nutrition: 26 Proteins	Nutrition: 27 Other	Toxins: 28 Human	Toxins: 29 Plant
Rickels	1977			X											X		X					X								
Rogers	1977			X									X									X								

Onions

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Literature Citations

Peanuts

Arachis hypogaea

REFERENCE CITED		LOCATION			EXPERIMENT VARIABLES															DATA OBTAINED										
					Radiation			Temperature						Media						Production						Nutrition			Toxin	
		Growth Chambers	Greenhouse	Field	Level	Photoperiod	Spectrum	Air	Soil	Leaf	Carbon dioxide	Humidity	Spacing & Growth Proc.	Type	Nutrients	pH	Soil potential & water stress	Tissue culture	Chemical hormones	Tops	Roots	Edible	Oxygen (carbon dioxide uptake)	Water		Carbohydrates	Proteins	Other	Human	Plant
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Cox	1979	X						X														X								
Diener & Davis	1969	X																											X	
Milov & Novikova	1975	X																				X	X	X			X	X		
Pallas & Samish	1974	X			X																		X							
Tsuno	1975			X								X											X	X						
Wood	1968		X					X												X		X								
Wynne et. al.	1973	X				X		X												X		X								
Wynne & Emery	1974	X				X																X								

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Literature Citations

Peas

<u>Pisum sativum</u>

REFERENCE CITED		LOCATION			EXPERIMENT VARIABLES															DATA OBTAINED										
					Radiation			Temperature						Media						Production						Nutrition			Toxin	
		Growth Chambers	Greenhouse	Field	Level	Photoperiod	Spectrum	Air	Soil	Leaf	Carbon dioxide	Humidity	Spacing & Growth Proc.	Type	Nutrients	pH	Soil potential & water stress	Tissue culture	Chemical hormones	Tops	Roots	Edible	Oxygen (carbon dioxide uptake)	Water		Carbohydrates	Proteins	Other	Human	Plant
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Dolan	1972	X			X	X		X												X										
Dolan	1973	X			X	X		X												X										
McLean, et. al.	1974	X													X		X			X		X					X			
Miller, et. al.	1977		X														X			X		X								
Summerfield, et. al.	1977	X											X																	

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Literature Citations

Rice

<u>Oryza sativa</u>

REFERENCE CITED		LOCATION			EXPERIMENT VARIABLES																DATA OBTAINED										
					Radiation			Temperature						Media							Production						Nutrition			Toxins	
		Growth Chambers	Greenhouse	Field	Level	Photoperiod	Spectrum	Air	Soil	Leaf	Carbon dioxide	Humidity	Spacing & Growth Proc.	Type	Nutrients	pH	Soil potential & water stress	Tissue culture	Chemical hormones	Tops	Roots	Edible	Oxygen (carbon dioxide uptake)	Water		Carbohydrates	Proteins	Other	Human	Plant
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Cock & Yoshida	1973		X								X											X								
Hanada	1974	X			X			X												X										
Haneda	1972	X						X																						
Hosoi	1975	X				X		X							X							X								
Int. Rice Inst.	1976	X	X	X	X	X		X			X	X					X			X		X	X	X		X	X	X		
Int. Rice Inst.	1976-1979	X	X	X	X	X		X			X	X	X		X		X			X	X	X		X		X	X	X		
Ishizuka	1979			X																		X								
Johnson & Diaz	1973	X											X									X								
Lin & Chen	1977		X					X												X		X	X							
Ojha & Pande	1976	X																		X										
Sarkar & Sircar	1975	X				X	X													X										
Sato	1971		X		X							X										X								
Sato et. al.	1974		X		X			X				X										X								
Sato & Takahashi	1971		X		X	X		X														X								
Shanghai Inst.	1977	X						X												X		X								
Singh	1973	X			X															X										
Singh & Pandya	1972	X				X														X										
Tsuno	1975			X								X											X	X						
Yoshida	1973	X						X												X										
Yoshida	1972	X	X	X	X			X			X									X		X	X							
Yoshida & Hara	1977	X			X			X												X		X								

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Soybeans

<u>Glycine max</u>

REFERENCE CITED		LOCATION			EXPERIMENT VARIABLES															DATA OBTAINED										
					Radiation			Temperature						Media						Production						Nutrition			Tox	
		1 Growth Chambers	2 Greenhouse	3 Field	4 Level	5 Photoperiod	6 Spectrum	7 Air	8 Soil	9 Leaf	10 Carbon dioxide	11 Humidity	12 Spacing & Growth Proc.	13 Type	14 Nutrients	15 pH	16 Soil potential & water stress	17 Tissue culture	18 Chemical hormones	19 Tops	20 Roots	21 Edible	22 Oxygen (carbon dioxide uptake)	23 Water	24	25 Carbohydrates	26 Proteins	27 Other	28 Human	29 Plant
Hofstra & Hesketh	1975	X			X						X											X	X							
Kaplan & Koller	1977	X																		X			X							
Lu & Yen	1975	X				X		X																						
Milov & Novikova	1975	X																				X	X	X			X	X		
Patterson & Kramer	1975	X		X	X																		X							
Patterson, et. al.	1977	X				X														X		X								
Peet, et. al.	1977	X											X									X								
Raper & Thomas	1978	X				X		X																						
Sionit & Kramer	1977	X																		X		X								
Summerfield, et. al.	1978																					X								
Thomas & Raper	1976	X				X																X								
Tibbitts & Kozlowski	1980	X																		X										
Tsuno	1975			X								X											X	X						
Warrington & Mitchell	1975	X			X		X													X						X	X			
Warrington, et. al.	1977	X						X												X										
Woodward	1976	X	X																	X			X							
Woodward & Begg	1976	X										X										X					X	X		

Soybeans

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Literature Citations

Strawberries

Fragaria x *ananassa*

REFERENCE CITED		LOCATION			EXPERIMENT VARIABLES															DATA OBTAINED										
					Radiation			Temperature						Media						Production						Nutrition			Toxins	
		Growth Chambers	Greenhouse	Field	Level	Photoperiod	Spectrum	Air	Soil	Leaf	Carbon dioxide	Humidity	Spacing & Growth Proc.	Type	Nutrients	pH	Soil potential & water stress	Tissue culture	Chemical hormones	Tops	Roots	Edible	Oxygen (carbon dioxide uptake)	Water		Carbohydrates	Proteins	Other	Human	Plant
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Albregts & Howard	1979			X									X							X		X								
Barritt	1974			X									X									X								
Bjurman	1974			X		X		X									X					X								
Bolton	1974			X																		X								
Brooks & Sargent	1976		X																			X								
Fujio & Amano	1974			X	X										X							X								
Hensley	1973			X									X							X										
Legeida et. al.	1976	X																X												
MacLachlan	1975			X									X																	
Moore et. al.	1975			X									X																	
Morris et. al.	1978			X									X																	
Morris et. al.	1979			X									X									X								
Tafazoli & Vince-Prue	1978		X			X														X										
Tafazoli & Shaybany	1978		X												X							X								

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Literature Citations

Sugar Beets

Beta vulgaris

REFERENCE CITED		Growth Chambers	Greenhouse	Field	Level	Photoperiod	Spectrum	Air	Soil	Leaf	Carbon dioxide	Humidity	Spacing & Growth Proc.	Type	Nutrients	pH	Soil potential & water stress	Tissue culture	Chemical hormones	Tops	Roots	Edible	Oxygen (carbon dioxide uptake)	Water		Carbohydrates	Proteins	Other	Human	Plant
		LOCATION			EXPERIMENT VARIABLES: Radiation			Temperature						Media						DATA OBTAINED: Production						Nutrition			Toxin	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Ford & Thorne	1967	X			X						X									X	X									
Hall & Loomis	1972	X		X																			X							
Milford & Lenton	1976	X				X														X	X									
Milov & Novikova	1975	X																				X	X	X		X	X	X		
Ohki & Ulrich	1973	X						X												X	X	X				X				
Singh	1978	X						X									X			X										
Snyder	1975																			X		X								
Ulrich	1952	X						X												X	X	X				X				
Ulrich	1955	X						X							X					X		X				X				
Ulrich	1958	X											X							X		X								
Ulrich	1961	X						X														X				X				
Ulrich & Ohki	1956	X														X				X		X						X		

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Literature Citations

Sweet Potato

Ipomoea batatas

REFERENCE CITED		LOCATION: Growth Chambers	LOCATION: Greenhouse	LOCATION: Field	Radiation: Level	Radiation: Photoperiod	Radiation: Spectrum	Temperature: Air	Temperature: Soil	Temperature: Leaf	Carbon dioxide	Humidity	Spacing & Growth Proc.	Media: Type	Media: Nutrients	Media: pH	Media: Soil potential & water stress	Tissue culture	Chemical hormones	Production: Tops	Production: Roots	Production: Edible	Production: Oxygen (carbon dioxide uptake)	Production: Water	Production: 24	Nutrition: Carbohydrates	Nutrition: Proteins	Nutrition: Other	Toxins: Human	Toxins: Plant
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Bell & Fuller	1965	X			X	X							X										X							
Enyi	1976			X																X		X								
Huett	1976			X																		X								
Lo & Wilson	1974a			X																X		X								
Lo & Wilson	1974b			X																		X								
Milov & Novikova	1973	X																		X		X	X	X		X	X	X		
Nikishanova	1978	X																				X								
Pluckett	1970			X											X							X								
Tsuno	1975			X				X				X											X	X		X				

Sweet Potato

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Literature Citations

Taro

Colocasia esculenta

REFERENCE CITED		LOCATION: 1 Growth Chambers	2 Greenhouse	3 Field	EXPERIMENT VARIABLES — Radiation: 4 Level	5 Photoperiod	6 Spectrum	Temperature: 7 Air	8 Soil	9 Leaf	10 Carbon dioxide	11 Humidity	12 Spacing & Growth Proc.	Media: 13 Type	14 Nutrients	15 pH	16 Soil potential & water stress	17 Tissue culture	18 Chemical hormones	DATA OBTAINED — Production: 19 Tops	20 Roots	21 Edible	22 Oxygen (carbon dioxide uptake)	23 Water	24	Nutrition: 25 Carbohydrates	26 Proteins	27 Other	Toxins: 28 Human	29 Plant
Bourke & Perry	1976												X							X		X								
El-Habbasha et. al.	1976												X		X					X		X								
Oliviera	1974																									X	X	X		
Plucknett	1970			X				X					X		X							X				X	X			
Raghu et. al.	1978																												X	
Sato et. al.	1978																			X			X							
Shaw	1975																			X										
Tsuno	1975			X								X								X			X							

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Literature Citations

Wheat

Triticum sativum

REFERENCE CITED		LOCATION: Growth Chambers (1)	Greenhouse (2)	Field (3)	EXPERIMENT VARIABLES: Radiation: Level (4)	Photoperiod (5)	Spectrum (6)	Temperature: Air (7)	Soil (8)	Leaf (9)	Carbon dioxide (10)	Humidity (11)	Spacing & Growth Proc. (12)	Media: Type (13)	Nutrients (14)	pH (15)	Soil potential & water stress (16)	Tissue culture (17)	Chemical hormones (18)	DATA OBTAINED: Production: Tops (19)	Roots (20)	Edible (21)	Oxygen (carbon dioxide uptake) (22)	Water (23)	(24)	Nutrition: Carbohydrates (25)	Proteins (26)	Other (27)	Toxins: Human (28)	Plant (29)
Ahmad	1973					X		X												X		X								
Anaya & Stolzy	1972	X														X	X													
Apel	1974	X									X											X								
Apel	1976	X																				X								
Austin & Edrich	1974		X				X													X										
Bagga & Rawson	1977		X					X												X		X								
Bird et. al.	1977	X						X			X																			
Evans	1978		X		X	X																X								
Focke	1975	X	X		X		X															X								
Ford & Thorne	1975	X			X			X														X								
Friend et. al.	1961	X					X													X										
Gifford	1977		X		X						X											X	X							
Gitel'son et. al.	1975	X																				X								
Keys et. al.	1977	X						X			X																			
Kolderup	1975a	X	X					X				X					X													
Kolderup	1975b		X					X									X					X					X			
Krenzer & Moss	1975	X						X			X											X								
Lipsett	1964		X												X							X						X		
Lynmore et. al.	1972	X			X											X				X										
Macdowall	1971	X			X						X									X	X		X							
Morgan	1977	X															X			X										
Neales & Nicholls	1978	X									X									X										
Partridge & Shaykewich	1972	X						X							X		X					X					X			
Passera & Albuzio	1978	X															X			X			X							
Pomeroy & Fowler	1973	X						X																						
Rawson & Bagga	1979		X					X												X		X								
Sofield et. al.	1977a	X			X			X														X								
Sofield et. al.	1977b	X													X		X					X						X		
Sojka et. al.	1975	X							X											X										
Spiertz	1974	X			X			X														X								
Spiertz	1978	X		X	X			X							X					X		X				X	X			
Warrington et. al.	1977	X						X												X		X								
Wunsche	1973	X	X		X			X												X		X								
Yang & Jong	1972	X						X				X					X							X						
Vil'yams & Rumyantseva	1978	X																		X	X		X							

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White Potato

<u>Solanum</u> <u>tuberosum</u>

REFERENCE CITED		LOCATION: Growth Chambers	LOCATION: Greenhouse	LOCATION: Field	EXPERIMENT VARIABLES: Radiation: Level	Radiation: Photoperiod	Radiation: Spectrum	Temperature: Air	Temperature: Soil	Temperature: Leaf	Carbon dioxide	Humidity	Spacing & Growth Proc.	Media: Type	Media: Nutrients	Media: pH	Media: Soil potential & water stress	Tissue culture	Chemical hormones	DATA OBTAINED: Production: Tops	Production: Roots	Production: Edible	Production: Oxygen (carbon dioxide uptake)	Production: Water	Production	Nutrition: Carbohydrates	Nutrition: Proteins	Nutrition: Other	Toxins: Human	Toxins: Plant
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
Frier	1977	X																		X		X	X							
Hammes et. al.	1974	X				X																X								
Krug & Wiese	1972	X															X					X								
Ku et. al.	1977	X			X			X			X												X							
Lynch & Rowberry	1977			X									X		X							X								
McCown & Kass	1977	X			X																	X								
McCown & Tanner	1980			X																		X								
Mendoza & Haynes	1976	X				X																X								
Milov & Novikova	1975	X																				X	X	X			X	X		
Nelson & Hwang	1975	X	X	X																				X						
Smith	1977			X	X			X					X	X	X		X			X		X				X	X			

White Potato

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Literature Citations

Winged Beans

<u>Psophocarpus tetragonolobus</u>

REFERENCE CITED		LOCATION: Growth Chambers 1	LOCATION: Greenhouse 2	LOCATION: Field 3	Radiation: Level 4	Radiation: Photoperiod 5	Radiation: Spectrum 6	Temperature: Air 7	Temperature: Soil 8	Temperature: Leaf 9	Carbon dioxide 10	Humidity 11	Spacing & Growth Proc. 12	Media: Type 13	Media: Nutrients 14	Media: pH 15	Media: Soil potential & water stress 16	Tissue culture 17	Chemical hormones 18	Production: Tops 19	Production: Roots 20	Production: Edible 21	Production: Oxygen (carbon dioxide uptake) 22	Production: Water 23	Production: 24	Nutrition: Carbohydrates 25	Nutrition: Proteins 26	Nutrition: Other 27	Toxins: Human 28	Toxins: Plant 29
Harding et. al.	1978																					X					X	X		
Herath & Ormrod	1979	X				X		X												X										
Karikari & Oteng	1977												X							X		X								
Khan & Erskine	1978			X																X		X								
Korte	1974																					X					X			
Levy	1978				X								X		X					X		X								
Martin & Delpin	1978																					X					X			
Nangju & Baudoin	1979			X																		X								
Nat. Acad. Sci.	1975	X													X											X	X			
Rachie	1978																			X		X								
Thompson	1978																			X										

The table's main column groups are LOCATION (1–3), EXPERIMENT VARIABLES (4–18) and DATA OBTAINED (19–29).

Winged Beans

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Literature Citations

Cultural Procedures

REFERENCE CITED		LOCATION: Growth Chambers 1	Greenhouse 2	Field 3	EXPERIMENT VARIABLES — Radiation: Level 4	Photoperiod 5	Spectrum 6	Temperature: Air 7	Soil 8	Leaf 9	Carbon dioxide 10	Humidity 11	Spacing & Growth Proc. 12	Media: Type 13	Nutrients 14	pH 15	Soil potential & water stress 16	Tissue culture 17	Chemical hormones 18	DATA OBTAINED — Production: Tops 19	Roots 20	Edible 21	Oxygen (carbon dioxide uptake) 22	Water 23	24	Nutrition: Carbohydrates 25	Proteins 26	Other 27	Toxins: Human 28	Plant 29
Asher	1978	X	X										X	X																
Asher & Edwards	1978														X															
Asher & Edwards	1978														X															
Asher et al.	1965												X		X															
Berry	1978														X					X										
Berry & Lunt	1979														X					X										
Berry & Wallace	1979														X															
Berry et al.	1977												X		X			X												
Bleak et al.	1974		X	X																		X								
Cooper	1979													X																
Dalrymple	1973		X																			X								
Deutch & Rasmussen	1974						X													X										
Dornling et al.	1975	X																												X
Edwards & Ascher	1974	X											X		X															
Enoch et al.	1970		X								X									X										
Ford & Thorne	1974											X																		
Furr et al.	1976												X		X															
Gitel'son et al.	1976	X											X									X				X	X			
Hasegawa	1977							X															X	X						
Hoffman	1973		X									X					X			X		X								
Huxley & Summerfield	1976					X		X												X		X								
Imai & Murata	1976										X									X										
Imai & Murata	1977										X									X										
Imai & Murata	1978										X									X										
Kretchmer	1977						X													X										
Krizek et al.	1974	X			X			X			X									X										

Literature Citations

Cultural Procedures continued

REFERENCE CITED		LOCATION			EXPERIMENT VARIABLES: Radiation			Temperature						Media						DATA OBTAINED: Production						Nutrition			Toxin	
		Growth Chambers	Greenhouse	Field	Level	Photoperiod	Spectrum	Air	Soil	Leaf	Carbon dioxide	Humidity	Spacing & Growth Proc.	Type	Nutrients	pH	Soil potential & water stress	Tissue culture	Chemical hormones	Tops	Roots	Edible	Oxygen (carbon dioxide uptake)	Water		Carbohydrates	Proteins	Other	Human	Plant
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29
O'Leary & Knecht	1974	X											X							X										
McCree	1972	X					X													X			X							
McKinney & Menser	1976	X																												X
Monteith	1976				X			X			X	X								X										
Moss & Loomis	1952			X																X			X							
Parkinson et al.	1974										X									X										
Rajan et al.	1971	X					X	X												X										
Rice	1974																			X										X
Rozov	1976	X											X							X		X								
Rozov & Silyutina	1977	X													X					X										
Terskov et al.	1974	X											X									X								
Tibbitts	1979											X								X			X	X						
Tsvetkova et al.	1971												X		X															
Tsvetkova et al.	1970	X												X								X								
Von Volkenburgh & Davies	1977	X		X																X				X						
Wallace et al.	1978												X	X						X										
Wallace et al.	1978												X	X	X															
Warrington	1972	X										X			X		X			X				X						
Warrington et al.	1978	X			X															X										
Warrington & Mitchell	1975	X					X													X										
Warrington et al.	1976	X			X		X	X												X										
Wittwer	1970		X								X									X		X								
Wittwer & Robb	1964		X								X									X		X								
Wilkes	1964	X											X							X		X								

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16. Abstract
This report summarizes the results of two workshops concerning the use of higher plants in Controlled Ecological Life Support Systems (CELSS). Criteria for plant selection were identified from these catergories: food production, nutrition, oxygen production and carbon dioxide utilization, water recycling, waste recycling, and other morphological and physiological considerations. The 27 participants recommended types of plant species suitable for use in CELSS, growing procedures, and research priorities. Also included are productivity values for selected plant species.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
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